S14-37

N91-27117 02229

p-15

STRUCTURAL CONCEPT STUDIES FOR
A HORIZONTAL CYLINDRICAL LUNAR HABITAT
AND
A LUNAR GUYED TOWER

Final Report

NASA/ASEE Summer Faculty Fellowship Program - 1990

Johnson Space Center

CS 214368

Prepared by: Paul K. Yin, Ph.D.,P.E.

Academic Rank: Associate Professor

University and Department: U.S. Coast Guard Academy
Engineering Department
New London, Conn. 06320

NASA/JSC

Directorate: Engineering

Division: Systems Engineering

Branch: Systems Definition

JSC Colleague: Clarence Bell, Ph.D.

Date Submitted: August 10, 1990

Contract Number: NGT-44-005-803

ABSTRACT

A conceptual structural design of a horizontal cylindrical lunar habitat is presented. The design includes the interior floor framing, the exterior support structure, the foundation mat, and the radiation shielding. Particular attention has been given on its efficiency in shipping and field erection, and on selection of structural materials.

Presented also is a conceptual design of a 2000-foot lunar guyed tower. A special field erection scheme is implemented in the design. In order to analyze the over-all column buckling of the mast, where its axial compression includes its own body weight, a simple numerical procedure is formulated in a form ready for coding in FORTRAN. Selection of structural materials, effect of temperature variations, dynamic response of the tower to moonquake, and guy anchoring system are discussed.

Proposed field erection concepts for the habitat and for the guyed tower are described.

INTRODUCTION

The Systems Engineering Division of the NASA/JSC is studying the development of permanent human presence on the moon. The development includes a relatively large habitat to provide long term human habitation, antenna towers for communication, among others.

The author designed the internal framing and the external foundation for a spherical inflatable lunar habitat during the summer of 1989 (A concept developed within NASA/JSC) [1,2]. With the experience gained on the first design, the Systems Engineering Division is considering a horizontal cylindrical habitat in addition to a spherical one. A conceptual structural design of this second concept (excluding the inflatable air enclosure) is presented in this report. The structure was analyzed by Ed Robertson of Systems Engineering Division, Systems Definition Branch using SDRC's IDEAS program [3]. An order-of-magnitude estimate of total structural dead weight is presented. The estimate is based on the structural members of Aluminum Lithium 8090-T8771 for the inside of the habitat and Magnesium alloy ZCM 711 [4] for the outside of the habitat, all within the AISC stress limitations [6] under the specified design live loads. The architectural and functional requirements including design live loads were provided by K. J. Kennedy of the Systems Engineering Division. The interior and exterior structural framings are to be pre-assembled, packaged for shipping, and automatically deployed into its final installed configuration with minimum effort required for field assemblage.

The development of permanent human presence on the moon also includes systems which may require installations of tower structures. Such systems may be for the lunar surface communication, power transmission, and area illumination. Given the radius of the lunar sphere the height of the towers is dictated by the distance between two adjacent towers. The longer the distance between towers, the higher the towers must be. While the communication area covered by a tower increases with the square of the tower's height the structural dead weight increases, generally speaking, with the cubic of the tower's height. This implies that the optimum height of the tower for lunar surface communication is zero. Further trade-off study on the use of towers for communication to the far side of the moon is needed including other factors and other possible alternatives.

For a surface area on the moon covered by a 30-mile radius (a limitation on an un-pressurized lunar rover) the height of the tower is approximately 2000 feet. A conceptual design of a 2000-foot lunar guyed tower, its materials, and field erection scheme are presented.

The installation of a 2000-foot guyed tower on the surface of the moon represents some unique design considerations. These considerations were studied and are discussed in this report.

THE HABITAT

General Concept

The basic concept of the horizontal cylindrical lunar habitat is similar to that of the spherical inflatable lunar habitat studied in the summer of 1989 [1,2] except that the over-all shape of the inflatable air enclosure is horizontal cylindrical, the regolith shielding is self supporting, the site preparation involves the removal of only the first one-foot layer of the lunar surface soil, and the framing is more efficient for shipping and field erection (Figure 1).

Design Requirements

The requirements, objectives and constraints are:

1. A minimized total structural dead weight.
2. Satisfaction of the Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings (AISC) [6].
3. Efficient for shipping and field erection.

4. A design live load of 50 earth pound per square foot (2.40 kPa) for the upper floor and 100 earth pound per square foot (4.79 kPa) for the lower floor (from K. J. Kennedy, Systems Engineering Division, JSC).
5. Architectural requirements as given by K.J. Kennedy of the Systems Engineering Division (Figure 1).

Interior Structural Framing

A highly efficient flat space truss (a pallet, developed by the Structural Engineering Division of JSC [12]) was determined to be suitable for both the two interior floors. The truss can collapse into a highly compact bundle for shipping and be automatically deployed into its final configuration at the site. The interior floor trusses for both the two levels (Figure 1) are about one-foot deep and are composed of 0.394-inch (1-cm) diameter round bars of Aluminum Lithium 8090-T8771 all of equal length for the upper and the lower cord planes and the 0.315-inch (0.8-cm) web members. Each floor truss is supported at ten points through which the area live loading is transferred across the fabric to the exterior support framing (Figure 1).

Exterior Support Structure

The support structure outside the habitat is designed so that the structure can be retracted into a bundle for shipping with its length slightly greater than the diameter of the cylindrical air enclosure (Figure 1).

The interior floor trusses and the exterior support structure were analyzed by Ed Robertson of the Systems Engineering Division, JSC using SDRC's IDEAS [3]. Under the design live loads, the maximum stresses and deflections were all found within AISC's limitations [6].

Foundation

The foundation mat provides enough bearing area for a factor of safety of 4 against ultimate bearing capacity of the lunar soil at about one-foot depth based on the lunar soil properties given by Mitchell, et.al. [7] using an empirical formula by Vesic [8]. The mat is designed so that it can be rolled into a bundle for shipping (Figure 1). The site preparation requires removal of the first one-foot layer of the lunar surface soil.

Radiation Shielding

The radiation shielding is essentially made of flat space trusses similar to the floor trusses inside the habitat, filled with lunar regolith, and each is wrapped with fabric to contain the regolith (Figure 1).

Materials

Aluminum Lithium 8090-T8771 is proposed for the interior floor trusses for its superior strength-to-weight ratio. Its relevant properties at room temperature are: [4,5]

Ultimate Strength:	64 ksi (441.28 MPa)
Yield Strength:	50 ksi (344.75 MPa)
Percent Elongation:	.5 to 2 %
Mass Density:	0.091 lb_m/in^3 (2,519 kg/m^3)
Modulus of Elasticity:	11.7×10^6 psi (80,672 MPa)
Thermal Expansion Coeff.:	$13 \times 10^{-6}/^oF$ ($23 \times 10^{-6}/^oC$)

Magnesium alloy ZCM 711, high in its strength-to-weight ratio, is selected for the exterior support structure and the foundation mat. This material has a relatively low combustion temperature and therefore is unsafe to use inside the habitat where oxygen is present. The relevant properties of this material are: [4,5]

Ultimate Strength:	40 ksi (275 MPa)
Yield Strength:	27 ksi (185 MPa)
Percent Elongation:	12 %
Mass Density:	0.065 lb_m/in^3 (1,795 kg/m^3)
Modulus of Elasticity:	6,500 ksi (45 GPa)
Thermal Expansion Coeff.:	$15 \times 10^{-6}/^oF$ ($27 \times 10^{-6}/^oC$)

Structural Dead Weight

The following weight estimate is based on a very basic conceptual design and therefore gives only a rough idea of the amount of materials to be shipped to the moon:

Upper Floor Truss:	1,320 lb_m	(600 kg)	of Al-Li
Lower Floor Truss:	950 lb_m	(430 kg)	of Al-Li
Support Structure:	560 lb_m	(254 kg)	of ZCM
Foundation Mat:	4,400 lb_m	(1,995 kg)	of ZCM
Total	7,230 lb_m	(3,280 kg)	

Field Erection

The following is a general outline of the field erection procedure with much further refinement yet to be developed.

1. A flat level surface is prepared at the site after the removal of the first one-foot layer of the lunar soil.
2. The top horizontal truss for the radiation shielding (roof)is fully stretched and is resting on the vertical

trusses (walls) which are not yet fully stretched.

3. The top horizontal truss is raised to its final elevation by jacking with the vertical trusses (walls) fully stretched to their final configuration simultaneously.
4. All fabric bags over the trusses were pre-attached and are now in their fully stretched shapes.
5. All trusses are filled with lunar regolith from top by a bucket elevator.
6. The foundation mat is laid.
7. The habitat module is placed on the mat.
8. The cylindrical air enclosure is inflated to its final volume while the pre-attached interior floors and the exterior support frame are also fully stretched to their final configuration.

Discussion

Aluminum-Lithium Al-Li 8090 is selected for the interior floor trusses for its superior strength-to-weight ratio to minimize shipping weight. The strength-to-weight ratio of Magnesium ZCM 711 is higher than that of Al-Li 8090 but ZCM 711 is unsafe to use inside the habitat due to its low combustion temperature. ZCM 711 is therefore selected for only the exterior support frame and the mat. Most Magnesium alloys including ZCM 711 are known to be weak in corrosion resistance. This presents no problem on the moon for there is no oxygen nor moisture outside the habitat.

While the Aluminum alloy is known to have superior resistance to embrittlement at low temperature [11] the Magnesium alloy ZCM 711 looses its ductility at low temperature and is therefore unsuited for load carrying in tension. It is therefore chosen for the support structure and the mat only where materials are primarily under compression.

The thickness of the first layer of the lunar surface soil to be removed was arbitrary in the design. Generally speaking, the soil bearing capacity increases with increase in depth but at the expense of increased site preparation.

THE GUYED TOWER

General Concept

The general concept of the proposed lunar guyed tower is essentially the same as that of typical guyed towers found on Earth (Figure 2). Unlike the design of tower structures on Earth, a lunar guyed tower requires no resistance to lateral wind loads for there is no wind on the moon. The only significant environmental lateral loading is perhaps due to a moonquake. It is possible, however, that significant stress and deformation occur due to severe daily (lunar) temperature variations. A structural analysis under this thermal loading (with the gravity loading properly combined) should be performed after the structure is better defined and a cyclic heat transfer and temperature-time history throughout the structure is assessed. In an effort to mitigate this temperature effect two different materials were selected, i.e., Magnesium alloy for the mast and Aluminum-Lithium for the guys. This temperature effect is further discussed in a later part of the report.

Design Requirements

Given below is a list of a very preliminary requirements/ constraints for the design of the lunar guyed tower.

1. A payload of 1,100 lb_m (500 kg) at approximately 2,000 feet above ground (given by M.L. Roberts, Systems Engineering Division, JSC).
2. A minimized total structural dead weight.
3. Satisfaction of the Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings (AISC) [6].
4. Efficient for shipping and field erection.
5. Resistant to moonquake.
6. Resistant to daily (lunar) temperature variations.
7. An elevator to the top of the tower.

The Mast

The mast is composed of identical 9-foot truss sections made of standard tubular members of Magnesium alloy CZM 711. The three cords and the braces make the cross sectional shape of the mast an equilateral triangle (Figure 2). The bottom 9-foot truss section is different from the rest (Figure 3) where larger openings are provided to facilitate traffic to the interior of the mast.

The Guys

The use of wire ropes made of Aluminum Lithium 8090 is proposed for the guy cables. A simple calculation (assuming uniform temperature variation throughout the mast and the guys) shows that, for a guy cable making an angle of approximately 58 degrees with horizontal and having its thermal expansion coefficient 23/27 of that of the mast [5], stresses induced in the guys and the mast are minimal due to the diurnal temperature variations. Using the formulas provided in [16] the maximum and minimum temperatures are approximately 240°F (388°K) and -248°F (118°K) respectively (depending also on the location on the lunar surface). These temperature extremes corresponds to a temperature range of 487°F (270°K) [16]. Since the metal tower is more reflective than the lunar surface the above temperature variation of the lunar surface can be used as the upper and lower bounds of temperature variation of the tower structure.

Since there is no lateral wind load on the lunar surface vertical locations of upper guy connections are determined solely by the buckling consideration of the mast. Thus the vertical spacings for the upper guy connections are determined by the Euler buckling formula [9] with a factor of safety of 2, i.e., $L = n\ (EI/2P)^{1/2}$ where P is conservatively taken as the axial compression at the lower end of the unbraced length L (the structural dead weight makes the axial compression at the lower end greater than at the upper end). To include the effect of the mast's own body weight on its critical buckling load a numerical procedure was formulated but is not presented in this report for lack of verification. Published information on column buckling including the column's own body weight can not be found at time of this writing [15]. This may be attributed to its relatively small effect in design (on Earth) as compared to that due to wind load.

The guys are to be sized to provide a lateral support capacity at their upper connections equal to 10% of the axial compression in the mast (to be considered fully effective). According to a recommended practice [10], the guys are to be pretensioned to 1/8 of their breaking strength. These pretensions in guys contribute to the axial compression in the mast (Figure 2).

Foundation

An equilateral triangular mat is sized to provide a bearing area at the base of the mast with a factor of safety of 4 against the ultimate bearing capacity of the lunar soil at approximately one foot below grade [7,8]. Immediately above the mat is a ball joint to effect a hinged support so that there will be no over-turning moment to be resisted by the foundation during a moonquake [14] (Figure 3).

All anchors of the guys should provide an ultimate up-lift capacity based on the breaking strength of the guys. A safety device is to be installed in series at the lower connection of each guy. The device should disengage when tension in the guy reaches a certain fraction of the guy's breaking strength. Experience in up-lift and lateral load capacities of piled or coil anchors on lunar surface and their installation is not available at time of this design study. Estimates of these capacities can be made using some existing numerical methods generally available within today's civil engineering practice. A less efficient alternative for the anchors would be the use of the so-called "deadman" concrete blocks. This anchoring alternative may become more attractive when cast-in-place lunar concrete becomes feasible.

Materials

The same Aluminum Lithium 8090-T8771 and Magnesium alloy ZCM 711 described earlier in this report for the lunar habitat are proposed for the guys and the mast respectively.

Structural Dead Weight

The total structural mass is estimated at about 9,000 lb_m with the following breakdowns: (excluding payload and anchors)

Mast:	8,620	lb_m (3,910 kg)	of ZCM
Guys:	250	lb_m (113 kg)	of Al-Li
Pedestal:	160	lb_m (73 kg)	of ZCM
Total:	9,030	lb_m (4,096 kg)	

Field Erection

The following field erection scheme for the guyed tower is proposed (Figure 4).

1. Prepare a flat level surface at the site after removal of the first one-foot layer of the lunar soil.
2. Set the foundation mat and the hinged-support assemblage (pedestal) on the prepared surface.
3. Position the top 9-foot section of the mast onto the pedestal.
4. Connect the three top-level guy cables to the top 9-foot section of the mast and to their anchors with some reels with a controlled tensioning device.
5. Install the hydraulic jack inside the mast.
6. Jack up the top 9-foot section of the mast until its bottom is clear for the next 9-foot section to be assembled around the hydraulic jack immediately below.
7. Assemble the next 9-foot section.
8. Repeat steps 6 and 7 and connect guy cables as designed until the last section.
9. Assemble the last bottom 9-foot section and secure to the support pedestal.
10. Remove the hydraulic jack.
11. Install the elevator.
12. Remove the three temporary members which were holding the support pedestal to the foundation mat.
13. Adjust tension in guys for mast's verticality.

Discussion

Due to the loss of ductility of the Magnesium alloy ZCM 711 at low temperature, ZCM 711 is selected only for the mast since the mast is primarily under compression. Aluminum-Lithium is selected for the guys (in tension) for their known ductility, modulus of elasticity, and strength preservation at both high and low temperatures [11,13]. Possibility of creeping of the mast and guys at the upper temperature extreme should be studied.

Numerical predictions of capacity and driveability of piled anchors are well developed for design on Earth. Applicability of these numerical techniques to lunar surfaces needs further investigation.

Dynamic amplification and response of the tower to moonquake should be analyzed and the structural integrity be verified at the two temperature extremes [14,16].

The in-situ guy cables are pretensioned to 1/8 of the breaking strength of the cable as generally practiced for guyed towers on Earth [10]. This pretensioning should be studied and possibly revised for guy cables on the moon.

Each 9-foot section of the mast can be made collapsible for shipping, stretched and assembled around the hydraulic jack at the site.

The daily (lunar) temperature variations of the structure can be reduced to a certain extent by coating the structure with some reflective material. The reflective coating reduces the net solar heat influx and thus lowers the upper extreme of the temperature variation.

It may be necessary to avoid direct contact between the mast (of Magnesium alloy) and the guys (of Aluminum-Lithium) at the upper guy connections for possible galvanic corrosion due to the two dissimilar metals.

A constant angle (approx. 60°) from the horizontal is proposed for all the guys to mitigate the stresses due to the temperature variations (in contrast to a single anchor for each vertical plane of guys, Figure 2).

REFERENCES

1. Yin, P.K., "A Preliminary Design of Interior Structure and Foundation of an Inflatable Lunar Habitat," Final Report, NASA/ASEE Summer Faculty Fellowship Program, Johnson Space Center, 1989.
2. Yin, P.K., "Structural Design of an Inflatable Lunar Habitat," Engineering, Construction, and Operations in Space II, Proceedings of Space 90, ASCE, 1990.
3. Structural Dynamics Research Corporation (SDRC), User's Guide, I-DEAS Level 4, Supertab .Engineering Analysis, 1988.
4. Charles, J.A.,Crane, F.A.A., "Candidate Materials for Aircraft Structures," Selection and Use of Engineering Materials, 2nd Ed., Section 15.4, Butterworths, 1989.
5. Gere, J.M., Timoshenko, S.P., "Mechanical Properties of Materials," Mechanics of Materials, 2nd Ed., Appendix H,
Brooks/Cole Engineering, 1984.
6. American Institute of Steel Construction, Inc. (AISC), Manual of Steel Construction, 8th Edition, 1980.
7. Mitchell, J.K. et.al., "Mechanical Properties of Lunar Soil: Density, Porosity, Cohesion, and Angle of Internal Friction," Proceedings of the Third Lunar Science Conference, Vol. 3, pp 3235-3253, The M.I.T. Press, 1972.
8. Vesic, A.S., "Bearing Capacity of Shallow Foundations," Foundation Engineering Handbook, Van Nostrand Reinhold Co., 1975.
9. Gere, J.M., Timoshenko, S.P., "Chapter 11: Columns," Mechanics of Materials, 2nd Ed., Brooks/Cole Engineering, 1984.
10. Zar, Max, "Section 24: Towers," Structural Engineering Handbook, McGraw-Hill Book Company, 1968.
11. Glazer, J., et al, "Cryogenic Mechanical Properties of Al-Cu-Li-Zr Alloy 2090," Presented at the International Cryogenic Materials Conference, Cambridge, MA, August 12-16, 1985.
12. Wesselski, C.J., "Expandable Pallet for Space Station Interface Attachments," U.S. Patent number 4,805,368, Feb. 21, 1989.
13. American Society of Metals (ASM), Metals Handbook Desk Edition, 1985.
14. McCaffrey, R.J., Hartmann, A.J., "Dynamics of Guyed Towers," J. of the Structural Division, Proceedings of the ASCE, Vol. 98, No. ST6, June, 1972.
15. Goldberg, J.E., Gaunt, J.T., "Stability of Guyed Towers," J. of Structural Division, Proceedings of the ASCE, Vol. 99, No. ST4, April, 1973.
16. Binder, Allen, Lunar Data Base, Lockheed Engineering & Sciences Co. Inc., April, 1990.

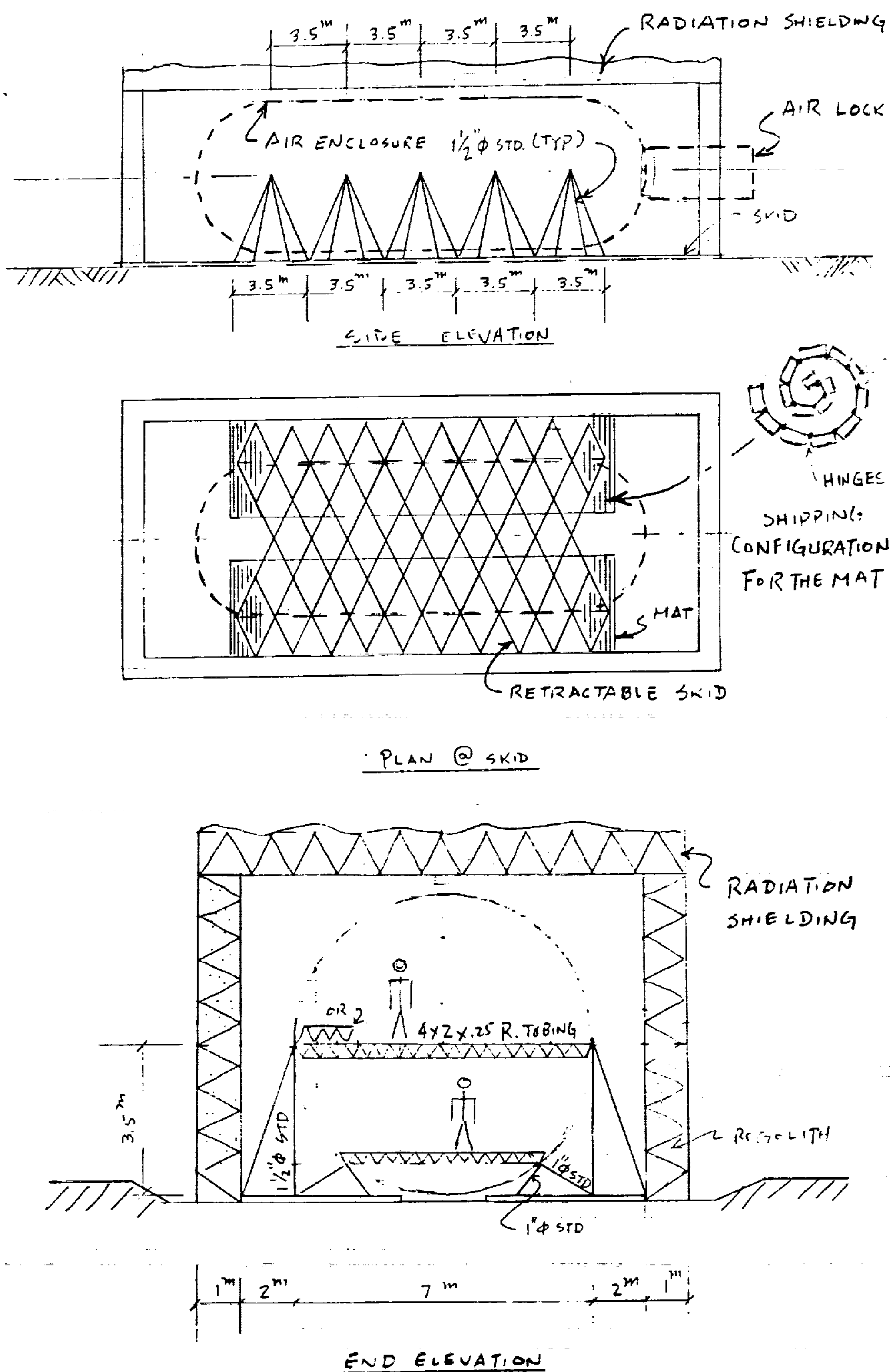

Figure 1. The horizontal cylindrical lunar habitat.

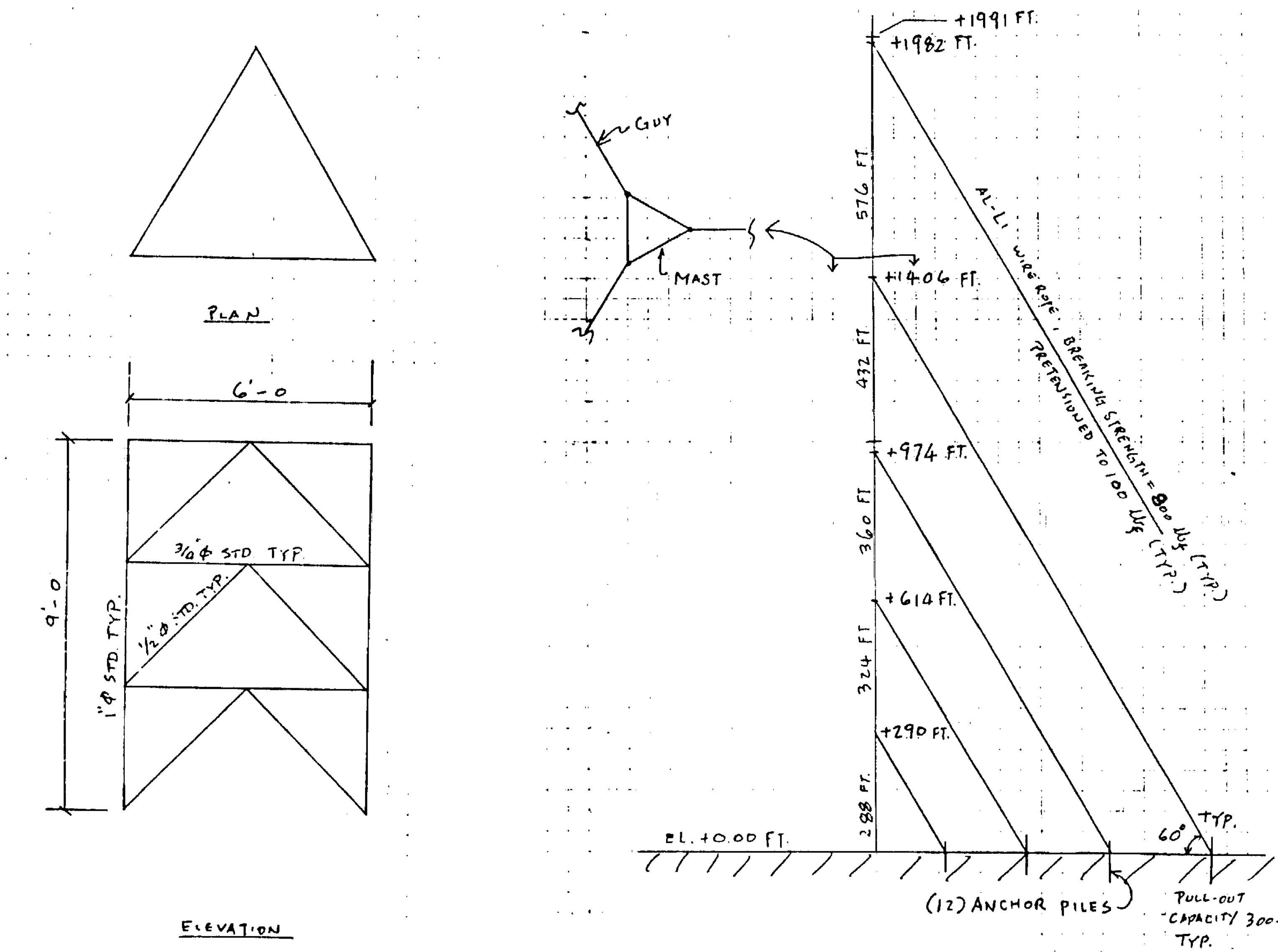

Figure 2. The guyed tower and the typical section of the mast.

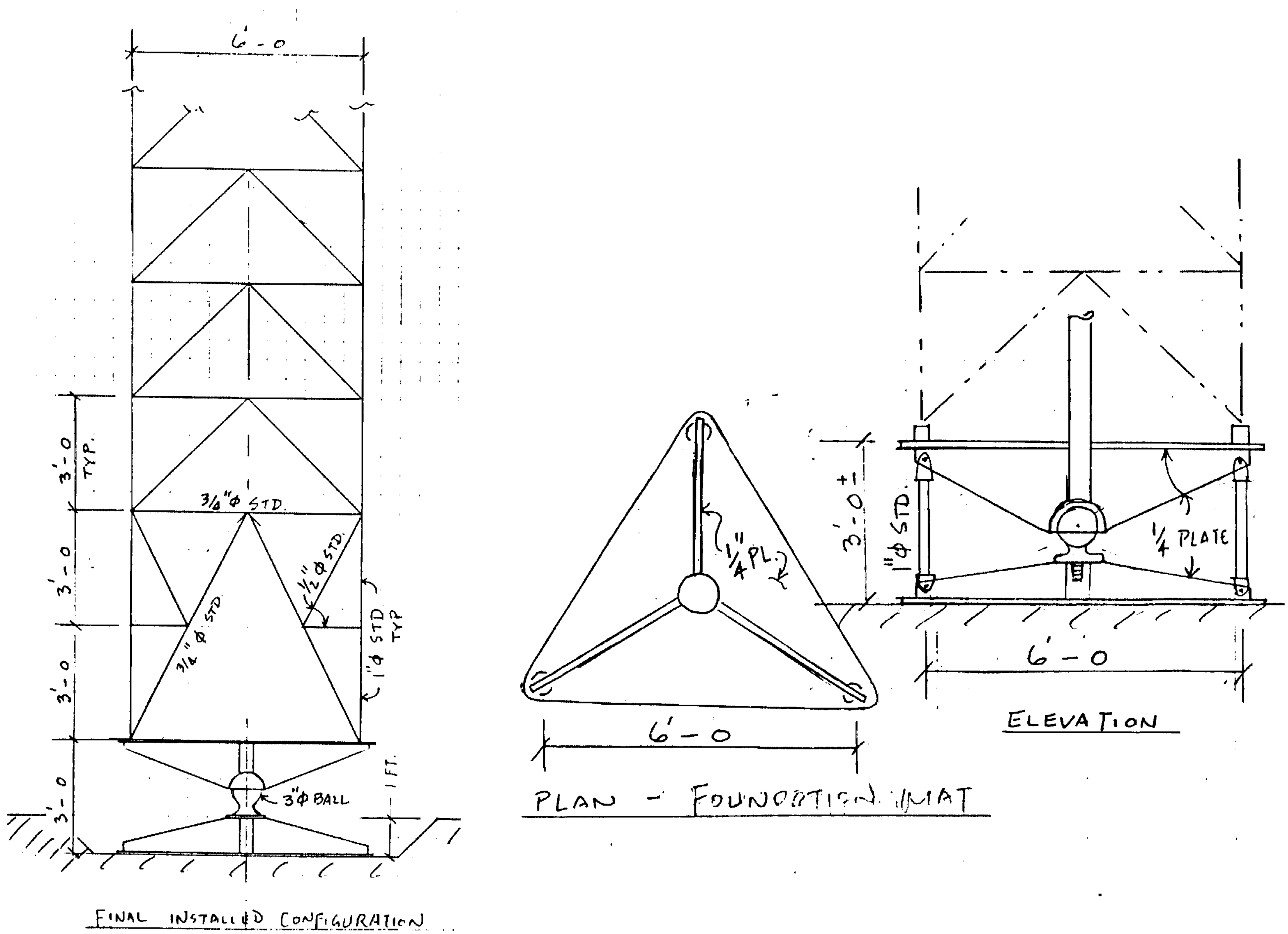

Figure 3. The guyed tower's foundation and support.

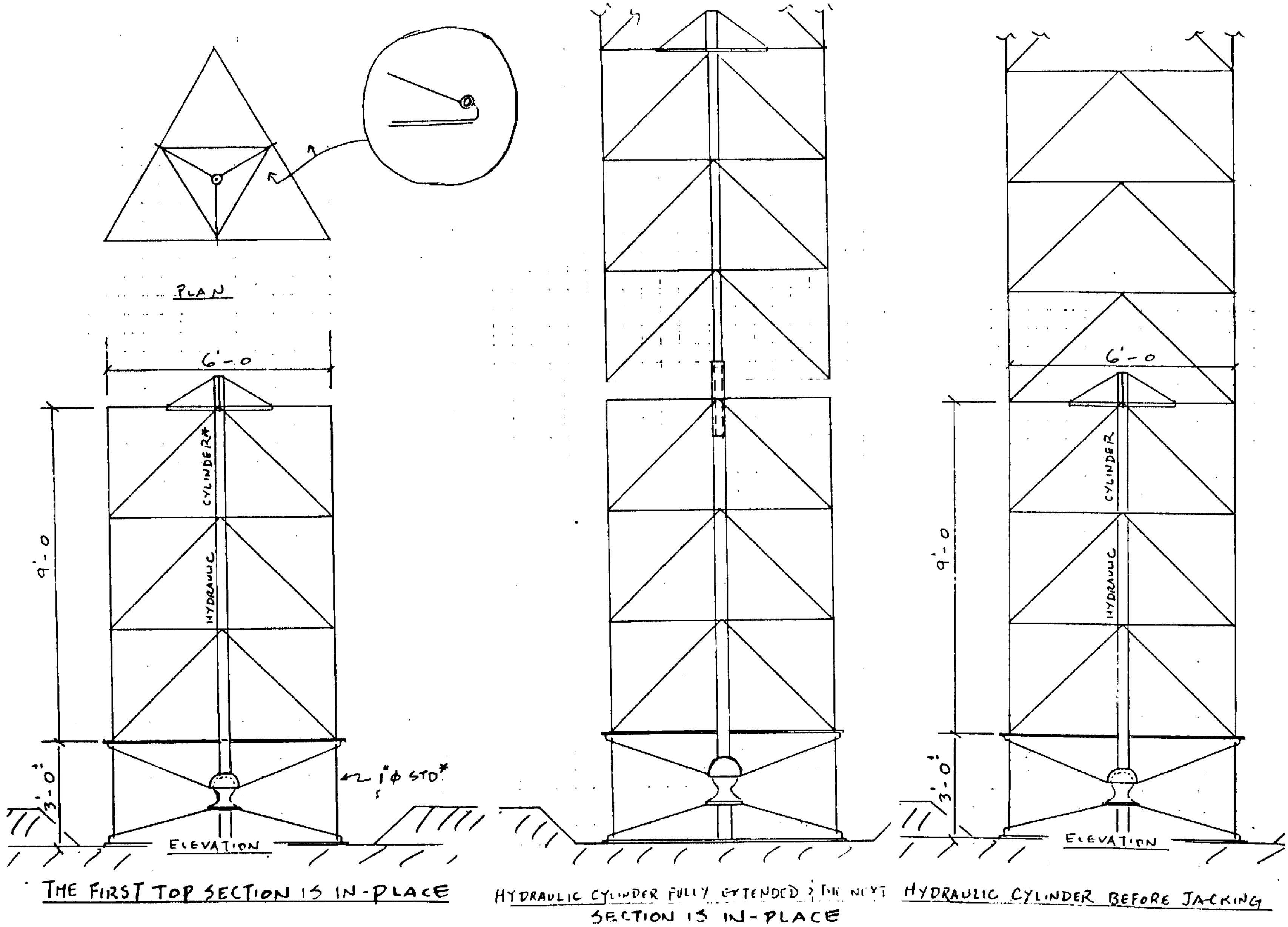

Figure 4. The guyed tower's installation sequence.